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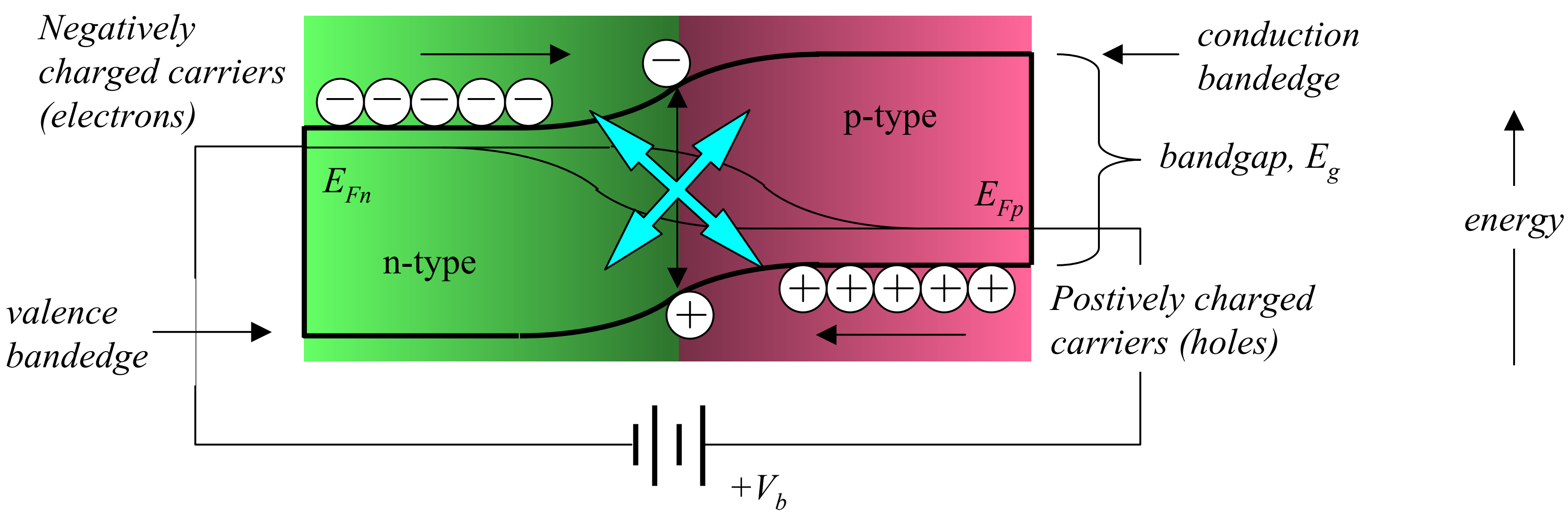
LIGHT FROM SILICON VALLEY

Progress and Future Direction of LED Technology

Mike Krames, Lumileds Lighting

SSL Workshop
13 Nov, 2003
Arlington, VA

What is a light-emitting diode?



- **Crystalline semiconductor atomic arrangement determines bandgap**
  - Specifies optical properties
- **Impurity doping provides p- and n-type regions**
- **At forward bias, injected electrons and holes recombine**
- **Energy may be released as radiative (light) or non-radiative (heat)**
- **Fundamentally non-destructive process**

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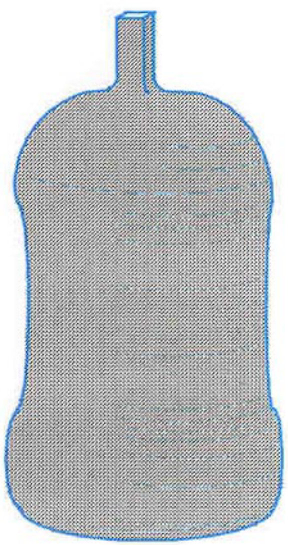
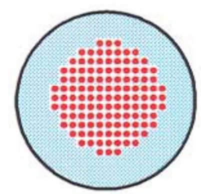
LED Fabrication

Bulk Substrate Crystal Growth & Machining → **Epitaxial Deposition of Light-Emitting Diodes** → **Wafer Fabrication** → **Die Fabrication** → **Final Product Assembly**

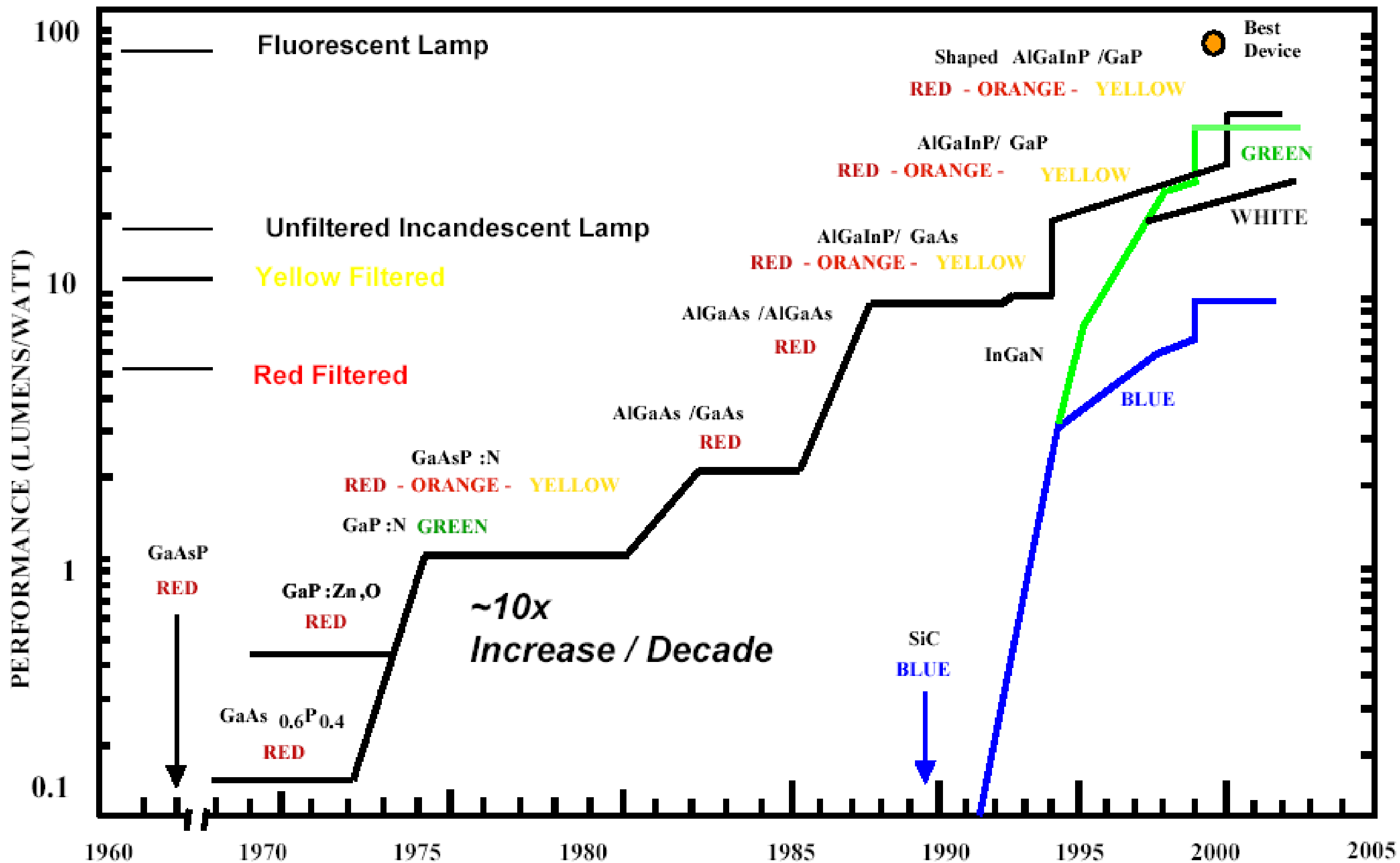


e.g., GaAs, Al_2O_3, SiC

e.g., metal-organic chemical vapor deposition (MOCVD)



Evolution of LED Efficiency



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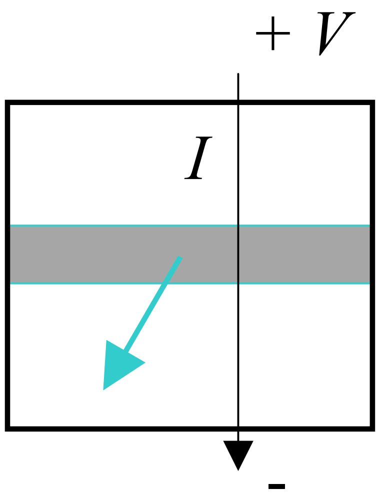
External Quantum Efficiency = Internal QE x Extraction Efficiency

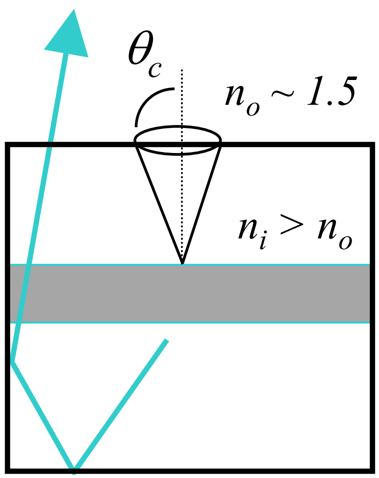
<u>Internal Quantum Efficiency</u>, η_{int} :

- material quality (defects, impurities)
- epitaxial layer structure and composition
- characteristics of material system
  - e.g. electronic bandstructure



<u>Extraction Efficiency</u>, C_{ext} :

- optical characteristics of chip
  - refractive index, $n_i > n_o$ (Snell's law)
  - "escape cone" ~ ¼ $(n_o/n_i)^2$ (5-10% / surface)
- internal absorption (losses) inside chip
- geometry of chip (thick- vs. thin-film; shape)
- degree of scattering



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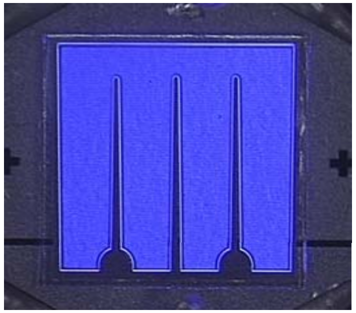
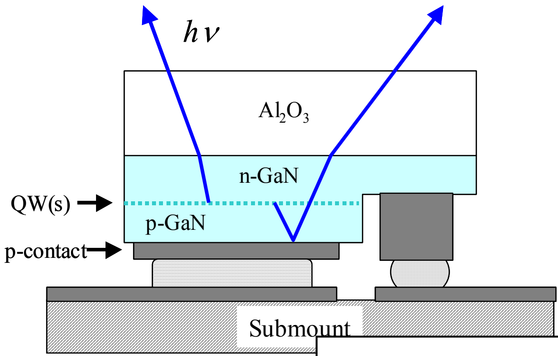
High Extraction Efficiency Structures





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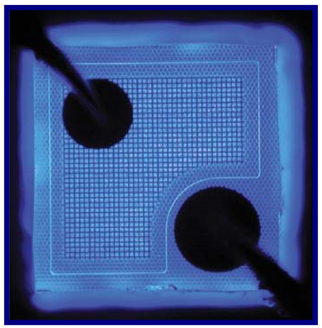
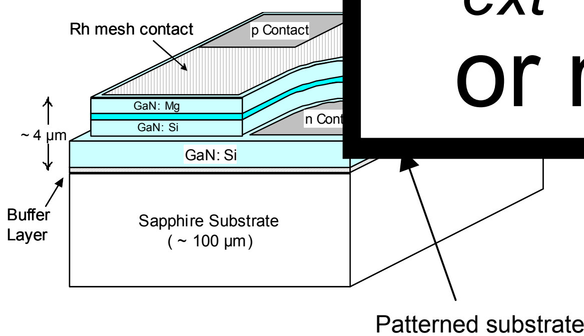
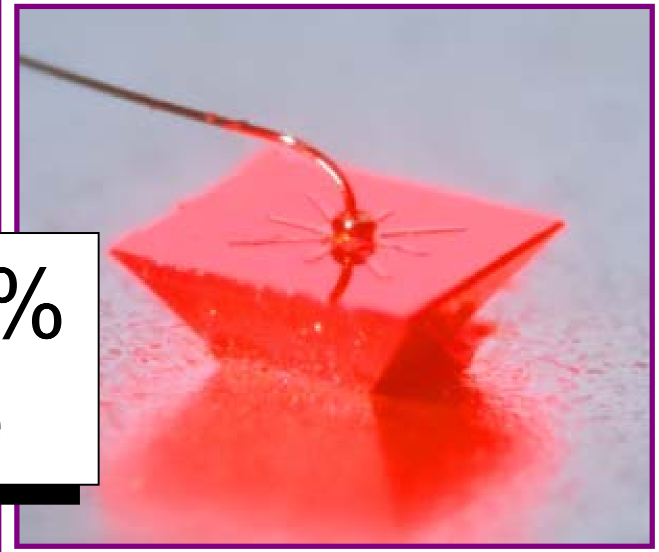




NICHIA

C_{ext} ~ 50% or more



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Many options:

- **Flipchip with reflective electrodes**
- **Conventional with transarent electrode & scattering features**
- **Thin-film with reflective intermetallic & scattering features**
- **Thick-film with die shaping**

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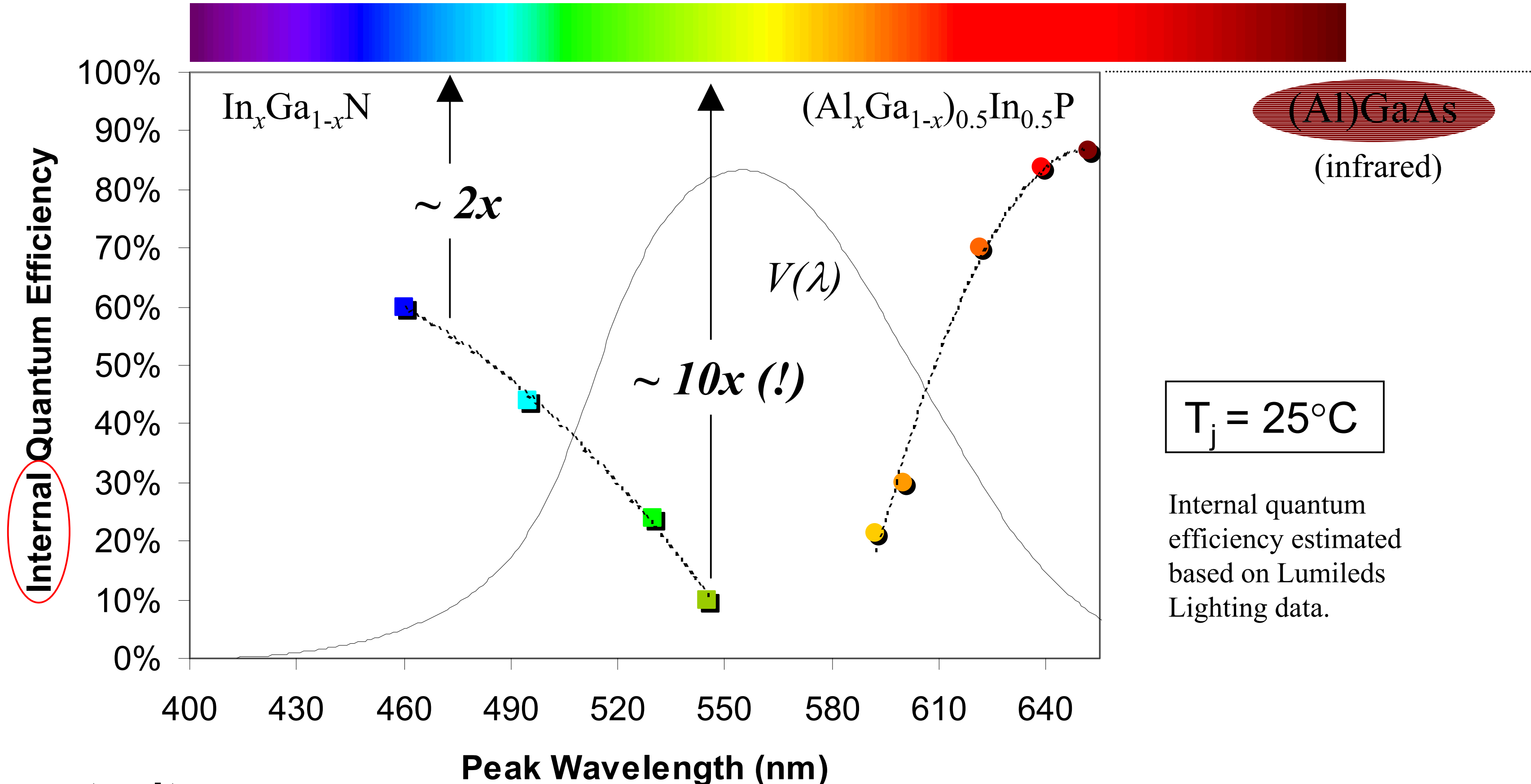
State of Art: Internal QE



Internal quantum efficiency estimated based on Lumileds Lighting data.

Opportunity:

- **Extraction efficiency: 2x increase max (theoretical limit)**
- **Internal quantum efficiency: up to 10x (!) at peak of eye sensitivity**
- **Example: At 100% η_{int} today's green LEDs would exceed <u>250 lm/W</u>**

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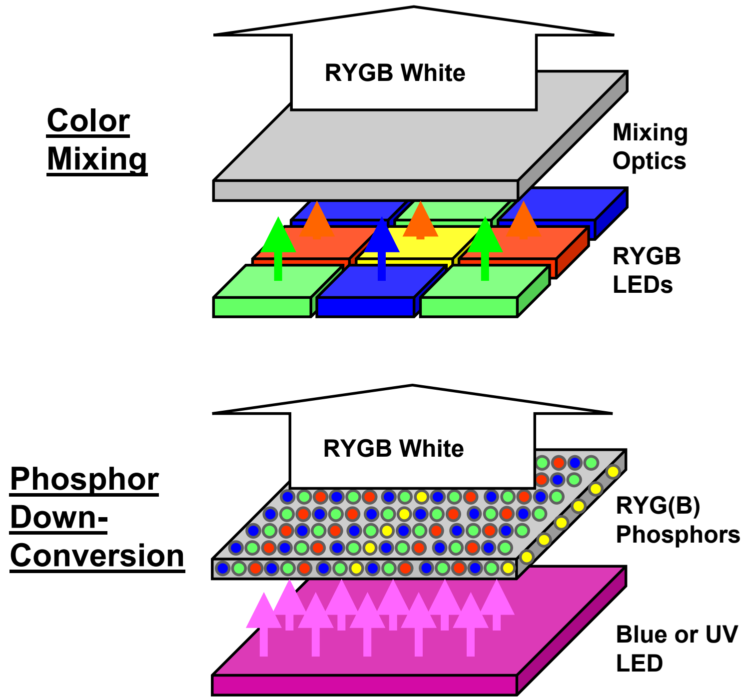
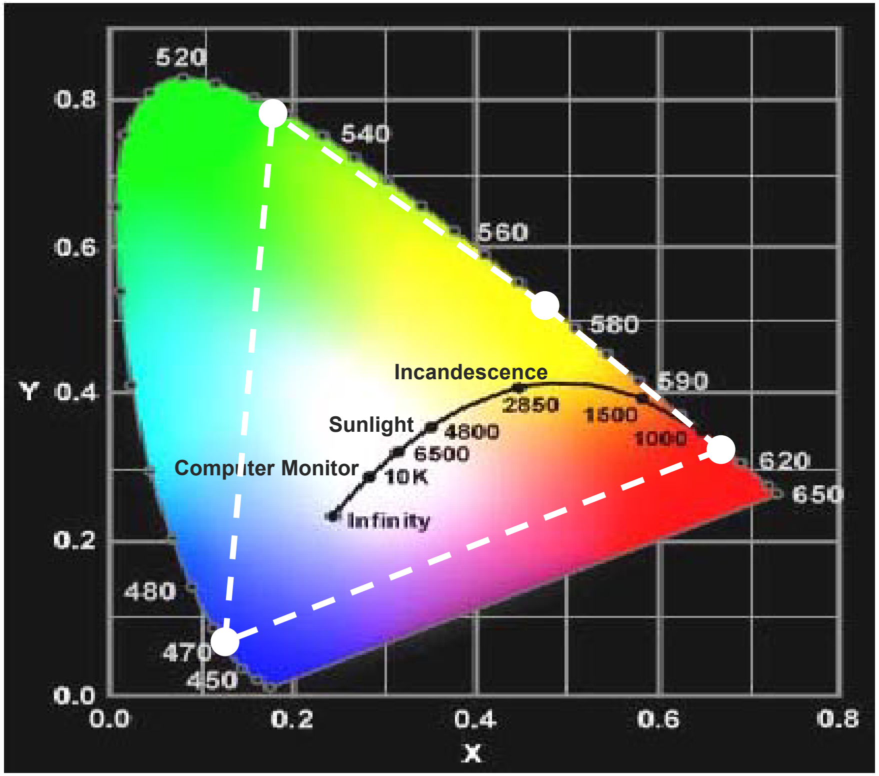
Making White





Images courtesy Jeff Tsao (Sandia National Labs).

Issues:

- **Phosphor conversion**
  - Quantum deficit, optical losses, new materials issues
- **Color mixing**
  - Optical losses (mixing), color uniformity, color control circuits

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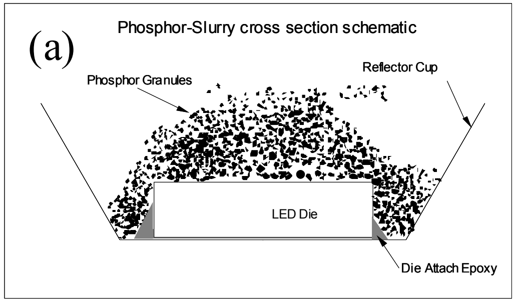
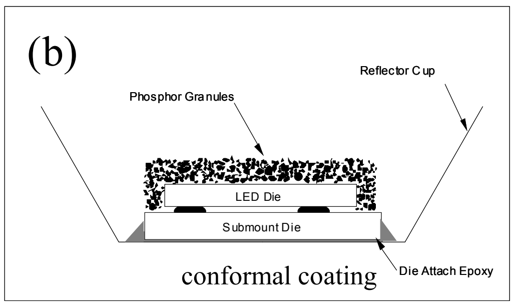
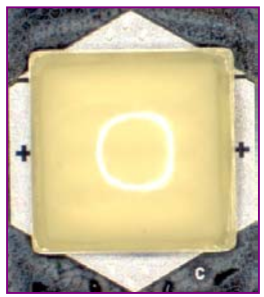
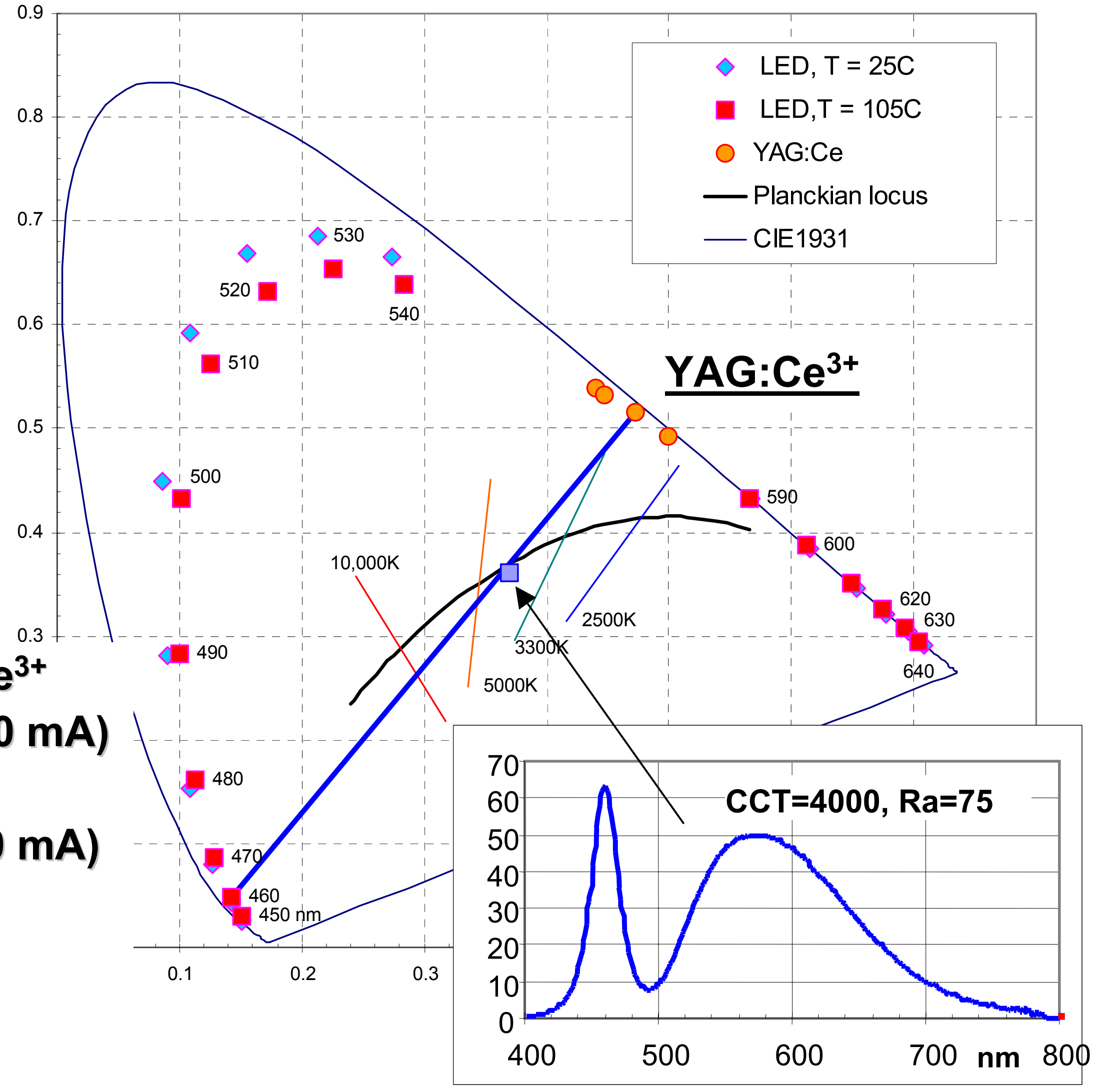
Phosphor-based White LEDs I









- **Predominant: blue LED + $YAG:Ce^{3+}$**
- **Production typical: ~ 30 lm/W (350 mA)**
  - Conversion efficiency ~ 60%
- **Laboratory results: > 60 lm/W (20 mA)**
- **Limitations:**
  - ~ 4000-8000K
  - Low CRI: ~75 (max.)

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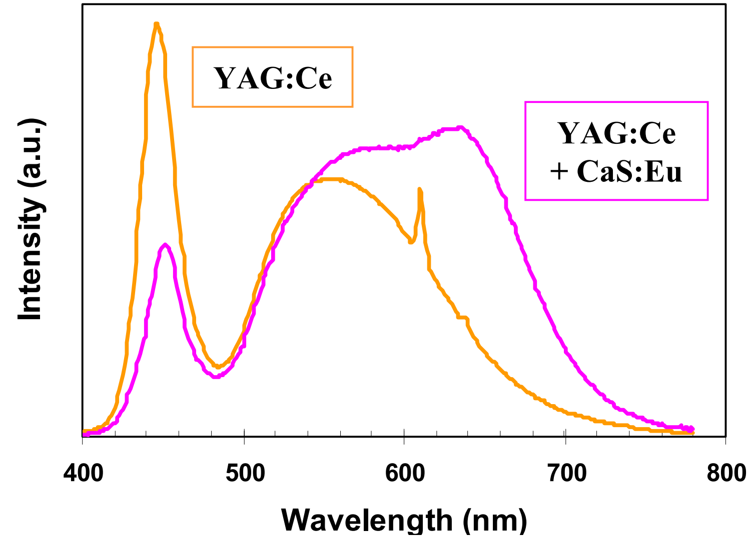
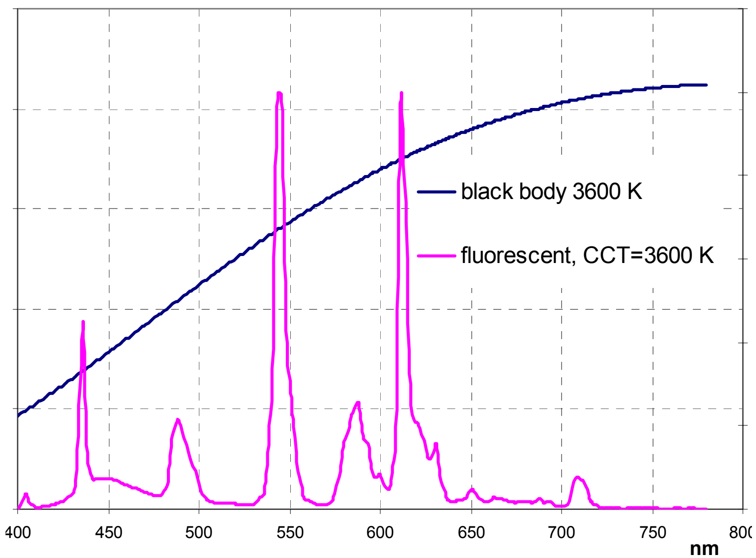
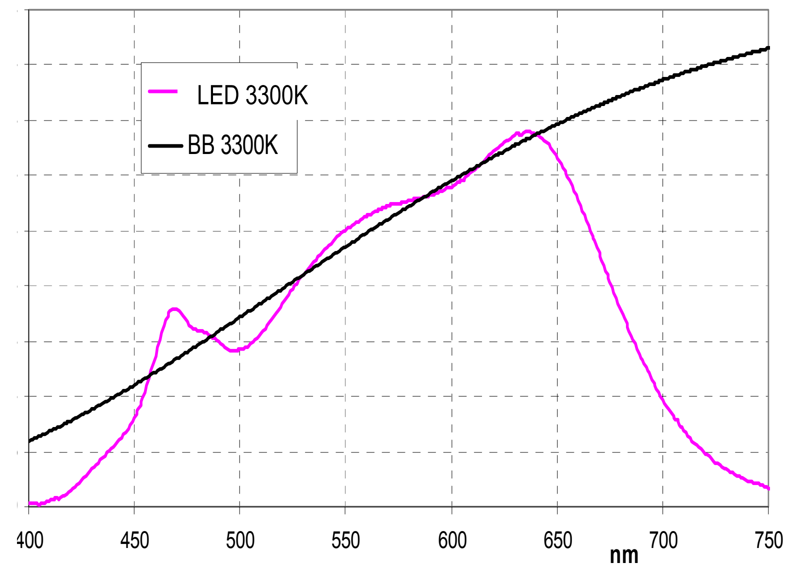
Phosphor-based LEDs for Illumination

- **Recent product release**
- **From YAG:Ce to YAG:Ce + CaS:Eu**
  - CRI: ~75 ~90
  - CCT: ~6000K ~3200K
  - η_L: ~30 lm/W ~20 lm/W
- **Excellent match to blackbody radiation**
- **Challenge: optical losses**
  - Conversion efficiency ~ 40%







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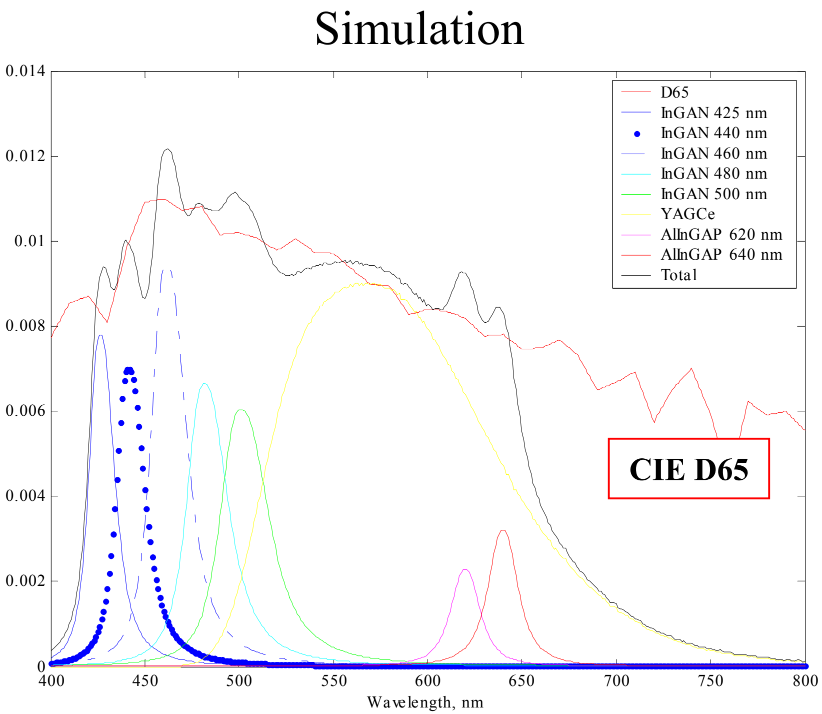
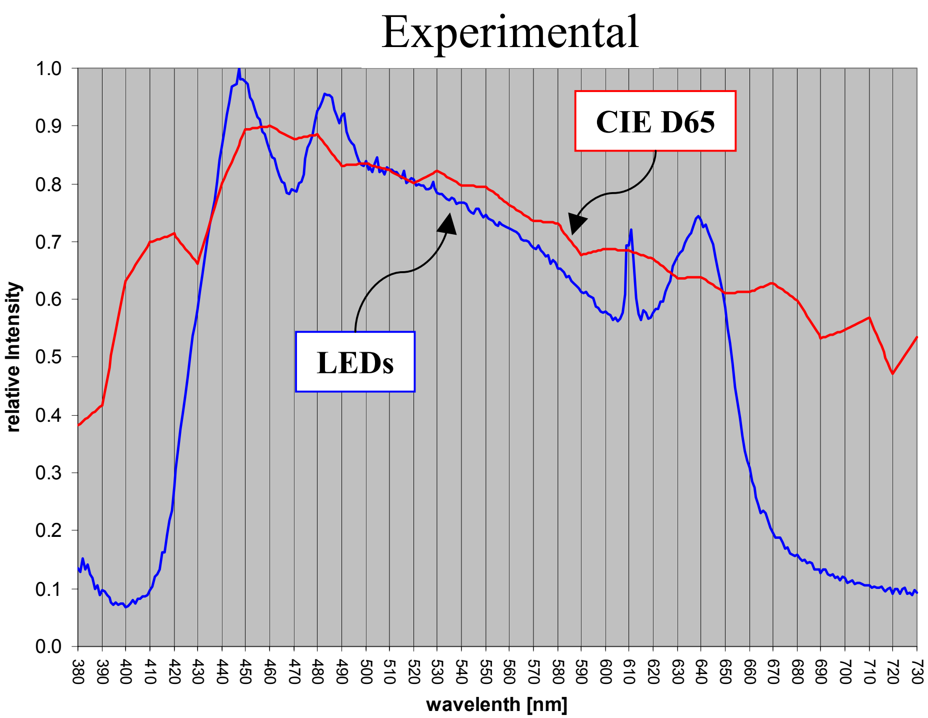
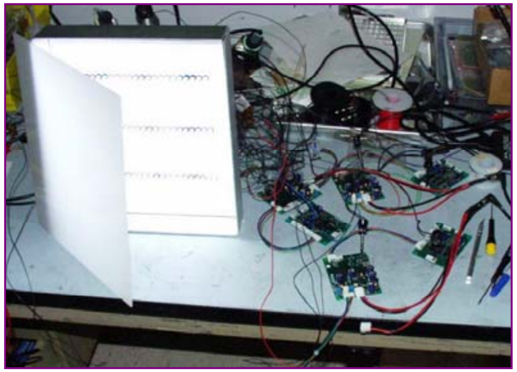
High-Fidelity, Tuneable White





- **Prototype: to match D65 from ~420 to ~650 nm**
- **Mix of InGaN, AlGaInP and phosphor-based LEDs**
- **Color rendering, CRI = 96 ($R_{a,14}$ = 94)**
- **RGB (3-line): CRI < 90**



DARPA

Advanced Technology Office

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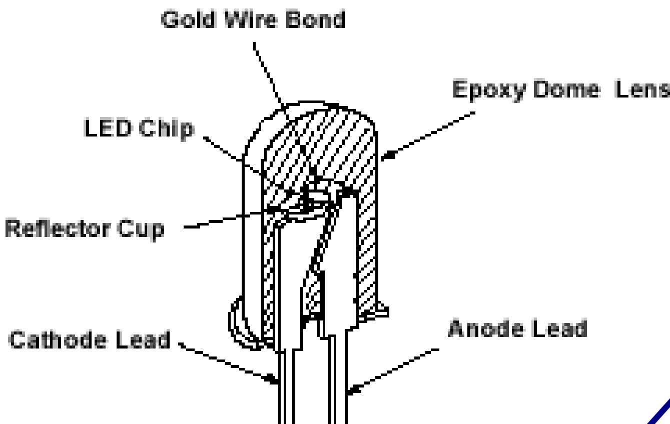
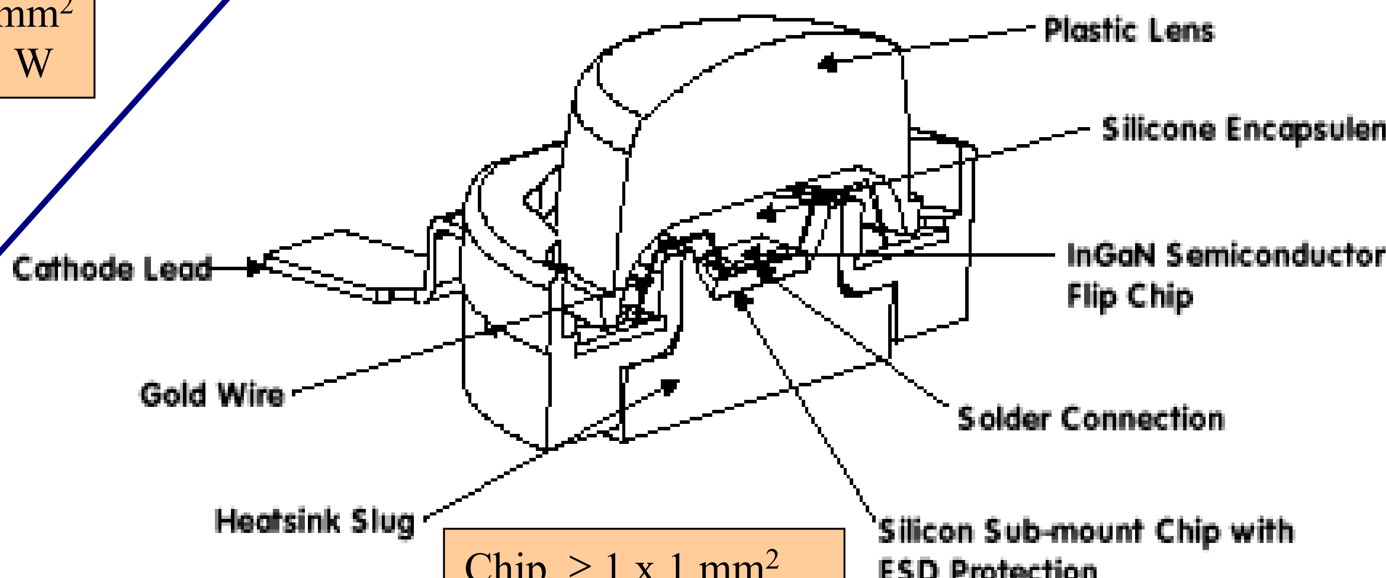
Packaging Technology



Chip ≤ 0.35 x 0.35 mm^2
Input power < ~ 0.1 W

5mm LED

LUXEON
A New World Of Light



Chip ≥ 1 x 1 mm^2
Input power ~ 1-5 W

Backlighting and Light Tile Concepts

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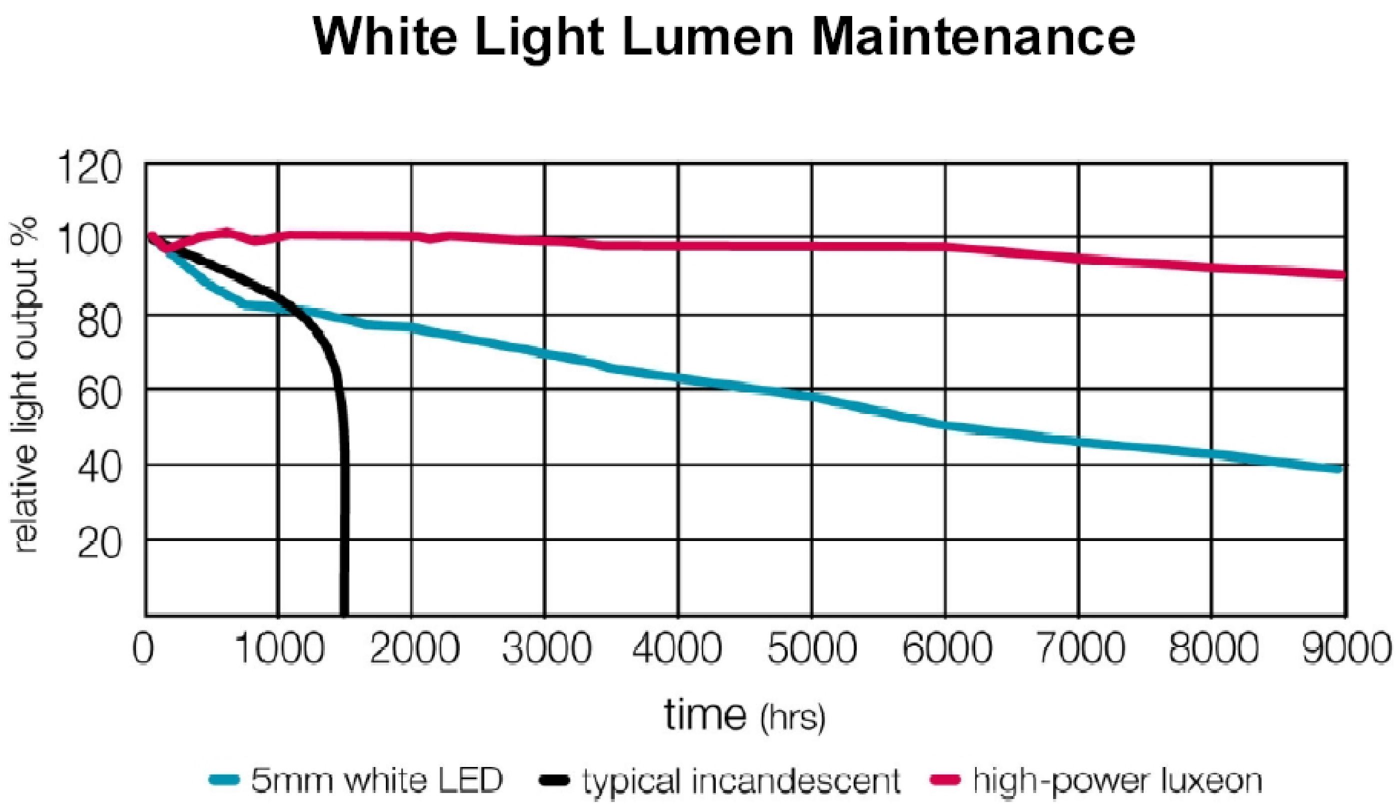
Reliability (1 Watt vs. "5 mm")



- **Standard 5 mm lamp LEDs degrade**
  - Epoxy yellowing
- **Luxeon 1 W (1x1 mm^2 chip; 350 mA)**
  - 50 khrs to 70% light output (T_j < 90°C)

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Higher Power LEDs (5 W)

15 W
110 lm/bulb
7 lm/W
Incandescent

4 W
145 lm/bulb
36 lm/W
Fluorescent

Luxeon™ 5W
150 lm/bulb
30 lm/W
2x2 mm^2 chip

- > 10 W: new packages under development

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Status vs. OIDA Roadmap

Product performance

		2002	2003	2007	2012	2020
Luminous Efficiency	lm/W	25	30 (20)	75	150	200
Lifetime	khrs	20	50*	20	100	100
Flux	lm	25	150 (24*)	200	1000	1500
Cost (Street Price)	$/klm	$200	$160*	$20	$5	$2
Color Rendering	Ra(8)	75	75 (90)	80	80	80
Markets Penetrated	-	low flux	low flux	incandescent	fluorescent	all
Source: OIDA 2002a			*1 W LEDs			

- **Outlook to 2007**
  - Efficiency → 2-4x
  - Cost → 8x (!)

Input power density → > 3x

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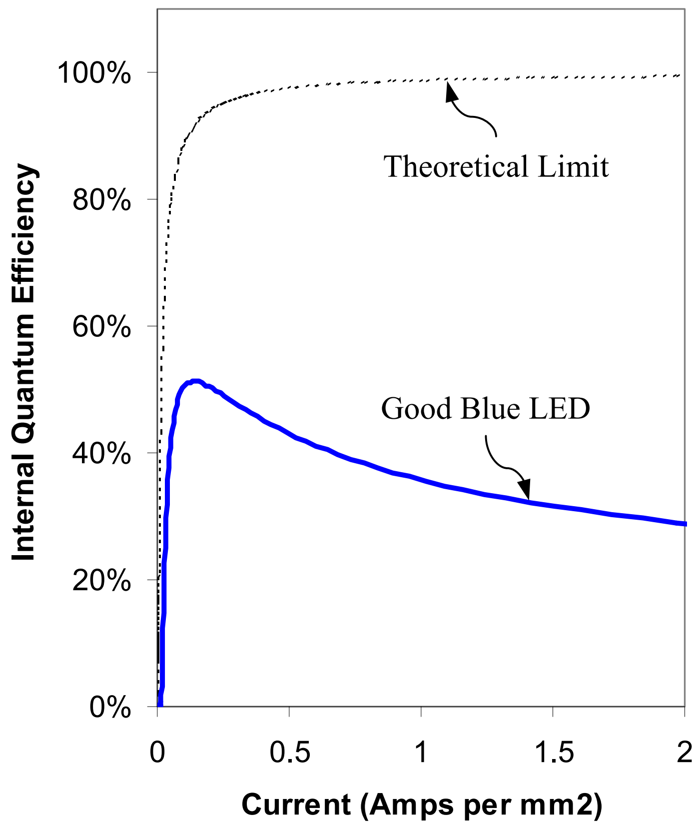
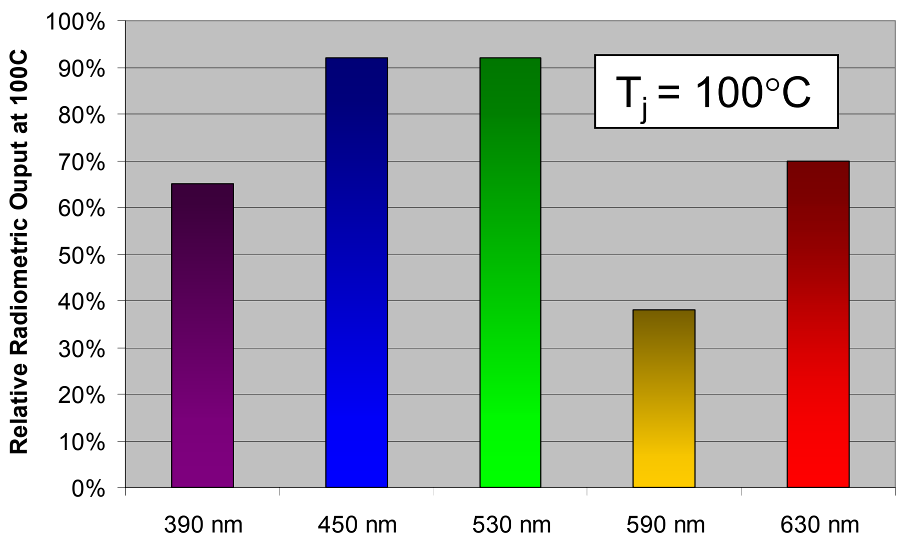
Increasing Power Density

- **Standard power LED**
  - 1 x 1 mm^2 chip: ~ 350 mA drive ea.
- **New power LED (Luxeon III)**
  - 1 x 1 mm^2 chip: up to ~ 1000 mA drive ea.
  - Typical: 80 lm white (high CCT)
  - ~ 21 lm/W (T_j = 25°C)
  - Lifetime: 20khrs (50% brightness)
- **Increasing power density costs efficiency**
- **Increasing temperature costs efficiency**





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The Future in Performance

- **Largest cost reduction lever is ever more lm per mm^2**
  - Requires increased power density
  - Must maintain high efficiency (energy savings)
    - Better material quality (internal quantum efficiency)
    - Improved device structures (high current, high temperature)
    - High conversion/mixing efficiency (to white)
    - Thermal management
    - Robust packaging materials (high flux, high temperature)

Summary I

- **Sustained rapid progress into 21st century**
  - Phosphor-based White
    - Single-phosphor (CRI~75)
      - Production LEDs available with ~ 30 lm/W
      - Laboratory results > 60 lm/W
      - 1000-lumen prototypes demonstrated
    - Multi-phosphor
      - Color rendering: CRI ~ 90 at 20 lm/W
  - Direct-based White
    - Demonstration high-fidelity white (D65 match, Ra>90)
    - Huge opportunity for improvement in green
    - Issues with temperature for AlGaInP
      - InGaN red?

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Summary II

- **Challenges ahead**
  - Decreased $/klm requires substantial increase in lumens per mm^2 of LED material
    - Better materials = largest gains
  - Improved manufacturing technology for lower costs
    - e.g., better III-nitride epitaxy using *in situ* tools
  - For substantial energy savings, must have technological entry point to large base of illumination market
    - Socket compatible solutions
    - How do we mate chip/level-1 platform to existing sockets?
      - Integrated thermal management
      - Imbedded circuitry for drive conditioning & color control

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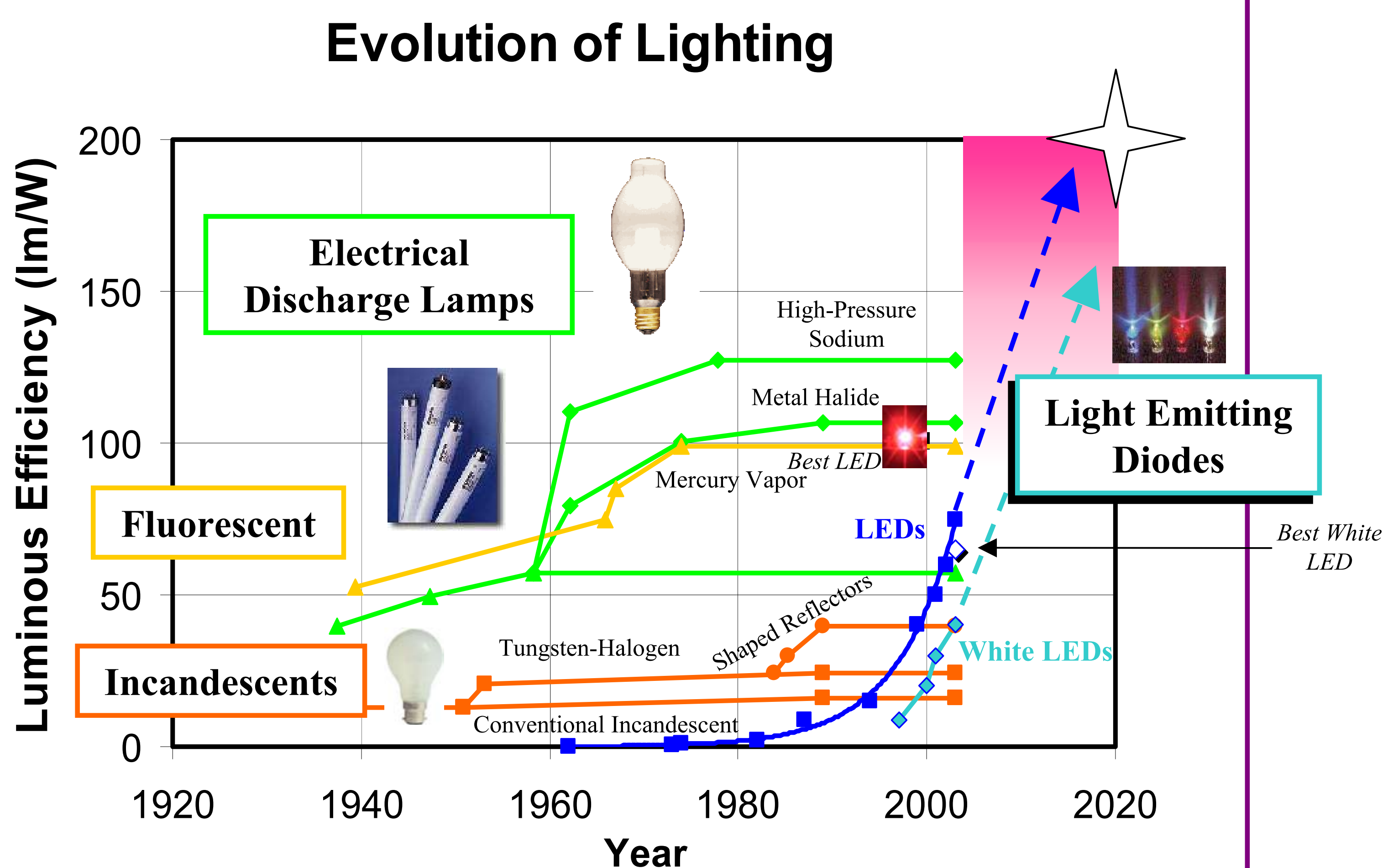
LEDs vs. Conventional Sources



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